

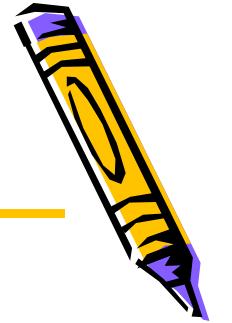


The Next Mainstream Programming Language: A Game Developer's Perspective

Tim Sweeney
Epic Games

Outline

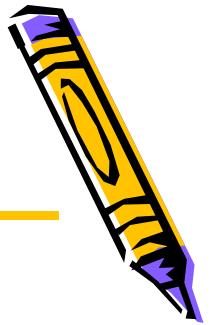
- Game Development
 - Typical Process
- What's in a game?
 - Game Simulation
 - Numeric Computation
 - Shading
- Where are today's languages failing?
 - Concurrency
 - Reliability



Game Development



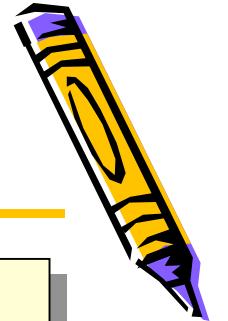
Game Development: Gears of War



- Resources
 - ~10 programmers
 - ~20 artists
 - ~24 month development cycle
 - ~\$10M budget
- Software Dependencies
 - 1 middleware game engine
 - ~20 middleware libraries
 - OS graphics APIs, sound, input, etc



Software Dependencies



Gears of War
Gameplay Code
~250,000 lines C++, script code

Unreal Engine 3
Middleware Game Engine
~250,000 lines C++ code

DirectX
Graphics

OpenAL
Audio

Ogg
Vorbis
Music
Codec

Speex
Speech
Codec

wx
Widgets
Window
Library

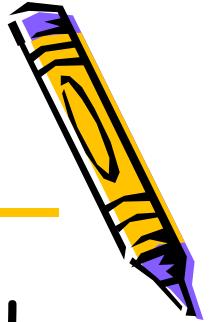
ZLib
Data
Compr-
ession

...

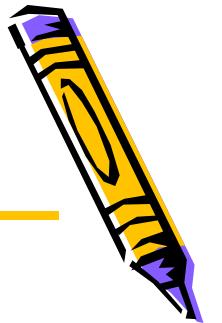


Game Development: Platforms

- The typical Unreal Engine 3 game will ship on:
 - Xbox 360
 - PlayStation 3
 - Windows
- Some will also ship on:
 - Linux
 - MacOS



What's in a game?



The obvious:

- Rendering
- Pixel shading
- Physics simulation, collision detection
- Game world simulation
- Artificial intelligence, path finding

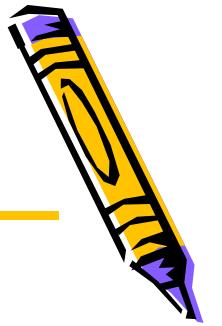
But it's not just fun and games:

- Data persistence with versioning, streaming
- Distributed Computing (multiplayer game simulation)
- Visual content authoring tools
- Scripting and compiler technology
- User interfaces



Three Kinds of Code

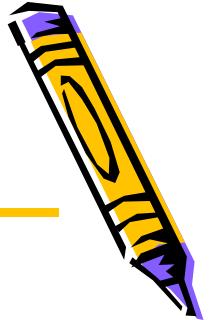
- Gameplay Simulation
- Numeric Computation
- Shading



Gameplay Simulation



Gameplay Simulation

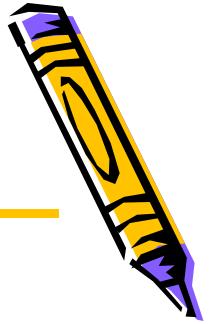


- Models the state of the game world as interacting objects evolve over time
- High-level, object-oriented code
- Written in C++ or scripting language
- Imperative programming style
- Usually garbage-collected

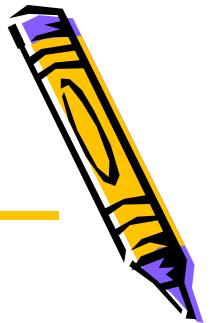


Gameplay Simulation - The Numbers

- 30-60 updates (frames) per second
- ~1000 distinct gameplay classes
 - Contain imperative state
 - Contain member functions
 - Highly dynamic
- ~10,000 active gameplay objects
- Each time a gameplay object is updated, it typically touches 5-10 other objects



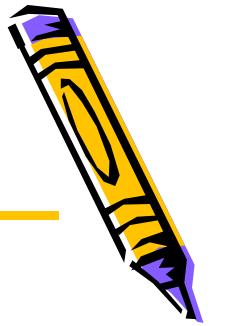
Numeric Computation



- Algorithms:
 - Scene graph traversal
 - Physics simulation
 - Collision Detection
 - Path Finding
 - Sound Propagation
- Low-level, high-performance code
- Written in C++ with SIMD intrinsics
- Essentially functional
 - Transforms a small input data set to a small output data set, making use of large constant data structures.



Shading



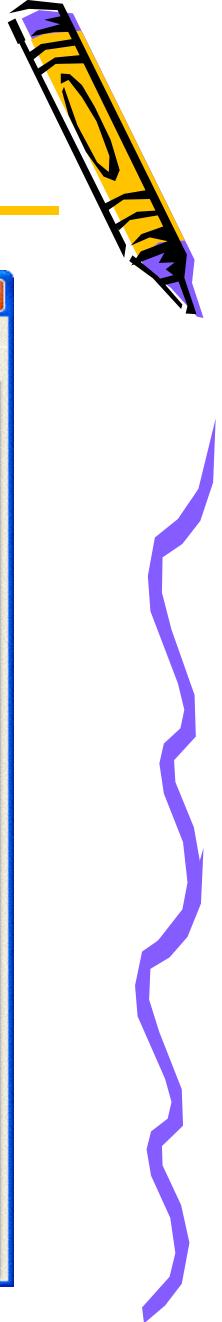
Shading



- Generates pixel and vertex attributes
- Written in HLSL/CG shading language
- Runs on the GPU
- Inherently data-parallel
 - Control flow is statically known
 - "Embarassingly Parallel"
 - Current GPU's are 16-wide to 48-wide!



Shading in HLSL



```
1 //pixel shader
2 float backProjectionCut: register(c2);
3 float Ka: register(c3);
4 float Kd: register(c4);
5 float Ks: register(c5);
6 float4 modelColor: register(c0);
7 float shadowBias: register(c1);
8
9 sampler ShadowMap: register(s0);
10 sampler SpotLight: register(s1);
11
12 float4 main(float3 normal: TEXCOORD0,
13             float3 lightVec: TEXCOORD1,
14             float3 viewVec: TEXCOORD2,
15             float4 shadowCrd: TEXCOORD3) : COLOR
16 {
17     normal = normalize(normal);
18     // Radial distance
19     float depth = length(lightVec);
20     // Normalizes light vector
21     lightVec /= depth;
22
23     // Standard lighting
24     float diffuse = saturate(dot(lightVec, normal));
25     float specular = pow(saturate(dot(reflect(-normalize(viewVec), normal), lightVec)), 16);
26
27     // The depth of the fragment closest to the light
28     float shadowMap = tex2Dproj(ShadowMap, shadowCrd);
29     // A spot image of the spotlight
30     float spotLight = tex2Dproj(SpotLight, shadowCrd);
31     // If the depth is larger than the stored depth, this fragment
32     // is not the closest to the light, that is we are in shadow.
33     // Otherwise, we're lit. Add a bias to avoid precision issues.
34     float shadow = (depth < shadowMap + shadowBias);
35
36     // Out color
37     return float4(shadow * specular, 1.0);
38 }
```

Shading - The Numbers

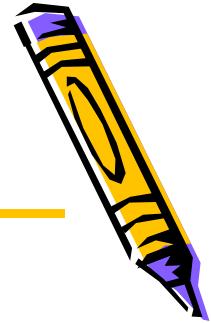


- Game runs at 30 FPS @ 1280x720p
- ~5,000 visible objects
- ~10M pixels rendered per frame
 - Per-pixel lighting and shadowing requires multiple rendering passes per object and per-light
- Typical pixel shader is ~100 instructions long
- Shader FPU's are 4-wide SIMD



~500 GFLOPS compute power

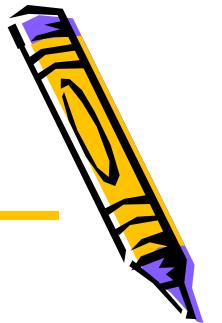
Three Kinds of Code



	Game Simulation	Numeric Computation	Shading
Languages	C++, Scripting	C++	CG, HLSL
CPU Budget	10%	90%	n/a
Lines of Code	250,000	250,000	10,000
FPU Usage	0.5 GFLOPS	5 GFLOPS	500 GFLOPS



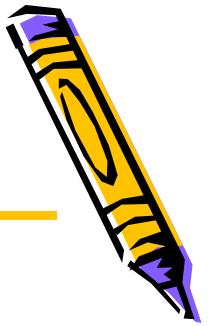
What are the hard problems?



- Performance
 - When updating 10,000 objects at 60 FPS, everything is performance-sensitive
- Modularity
 - Very important with ~10-20 middleware libraries per game
- Reliability
 - Error-prone language / type system leads to wasted effort finding trivial bugs
 - Significantly impacts productivity
- Concurrency
 - Hardware supports 6-8 threads
 - C++ is ill-equipped for concurrency



L



Performance

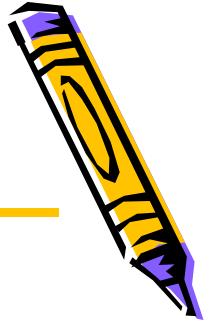


Performance

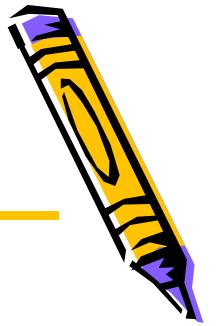
- When updating 10,000 objects at 60 FPS, everything is performance-sensitive
- But:
 - Productivity is just as important
 - Will gladly sacrifice 10% of our performance for 10% higher productivity
 - We never use assembly language
- There is not a simple set of "hotspots" to optimize!



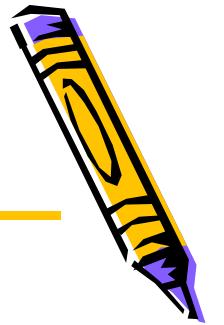
That's all!



Modularity



Unreal's game framework



Gameplay module

Base class of gameplay objects

Members

```
package UnrealEngine;

class Actor
{
    int Health;
    void TakeDamage(int Amount)
    {
        Health = Health - Amount;
        if (Health<0)
            Die();
    }
}

class Player extends Actor
{
    string PlayerName;
    socket NetworkConnection;
}
```



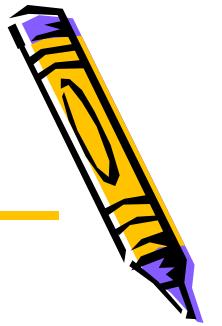
Game class hierarchy

Generic Game Framework

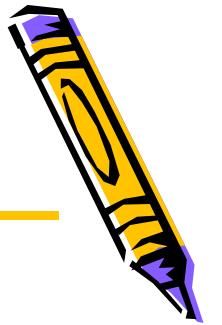
Actor
Player
Enemy
InventoryItem
Weapon

Game-Specific Framework Extension

Actor
Player
Enemy
Dragon
Troll
InventoryItem
Weapon
Sword
Crossbow



Software Frameworks



- The Problem:

Users of a framework
need to extend the functionality
of the framework's base classes!

- The workarounds:

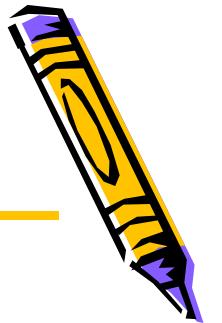
- Modify the source

...and modify it again with each new version

- Add references to payload classes, and
dynamically cast them at runtime to the
appropriate types.



Software Frameworks



- The Problem:

Users of a framework
want to extend the functionality
of the framework's base classes!

- The workarounds:

- Modify the source

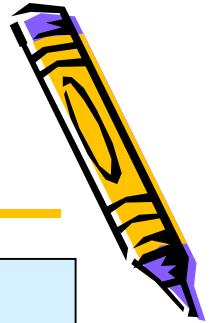
...and modify it again with each new version

- Add references to payload classes, and
dynamically cast them at runtime to the
appropriate types.

These are all error-prone:
Can the compiler help us here?



What we would like to write...



Base Framework

```
package Engine;

class Actor
{
    int Health;
    ...
}

class Player extends Actor
{
    ...
}

class Inventory extends Actor
{
    ...
}
```

Extended Framework

```
Package GearsOfWar extends Engine;

class Actor extends Engine.Actor
{
    // Here we can add new members
    // to the base class.
    ...
}

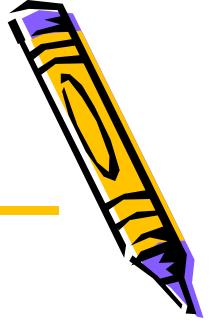
class Player extends Engine.Player
{
    // Thus virtually inherits from
    // GearsOfWar.Actor
    ...
}

class Gun extends GearsOfWar.Inventory
{
    ...
}
```



The basic goal:

To extend an entire software framework's class hierarchy in parallel, in an open-world system.



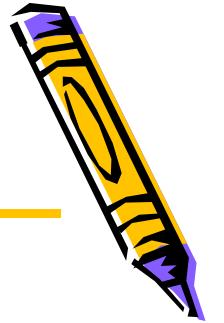
Reliability

Or:

If the compiler doesn't beep,
my program should work



Dynamic Failure in Mainstream Languages



Example (C#):

Given a vertex array and an index array, we read and transform the indexed vertices into a new array.

```
Vertex[] Transform (Vertex[] Vertices, int[] Indices, Matrix m)
{
    Vertex[] Result = new Vertex[Indices.length];
    for(int i=0; i<Indices.length; i++)
        Result[i] = Transform(m,Vertices[Indices[i]]);
    return Result;
};
```

What can possibly go wrong?



Dynamic Failure in Mainstream Languages

```
Vertex[] Transform (Vertex[] Vertices, int[] Indices, Matrix m)
{
    Vertex[] Result = new Vertex[Indices.length];
    for(int i=0; i<Indices.length; i++)
        Result[i] = Transform(m, Vertices[Indices[i]]);
    return Result;
}
```

Will the compiler
realize this can't fail?

Could dereference
a null pointer

Array access
might be out
of bounds

May contain indices
outside of the range of
the Vertex array

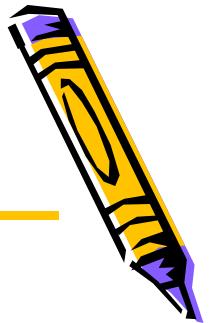
May be NULL

May be NULL

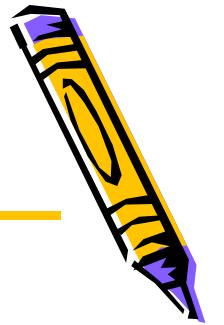
May be NULL



Our code is littered with runtime failure cases,
Yet the compiler remains silent!



Dynamic Failure in Mainstream Languages



Solved problems:

- Random memory overwrites
- Memory leaks

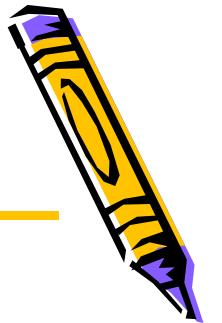
Solveable:

- Accessing arrays out-of-bounds
- Dereferencing null pointers
- Integer overflow
- Accessing uninitialized variables

50% of the bugs in Unreal can be traced to these problems!



What we would like to write...



An index buffer containing natural numbers less than n

An array of exactly known size

Universally quantify over
all natural numbers

```
Transform{n:nat} (Vertices:[n]Vertex, Indices:[]nat<n, m:Matrix) : []Vertex =  
  for each(i in Indices)  
    Transform(m, Vertices[i])
```

Haskell-style array
comprehension

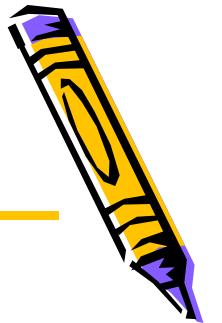


The only possible failure mode:

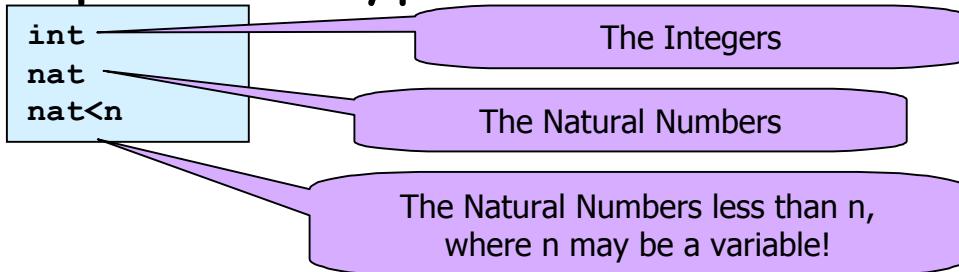
divergence, if the call to
Transform diverges.



How might this work?



- **Dependent types**



- **Dependent functions**

```
Sum(n:nat, xs:[n]int)=..  
a=Sum(3, [7, 8, 9])
```

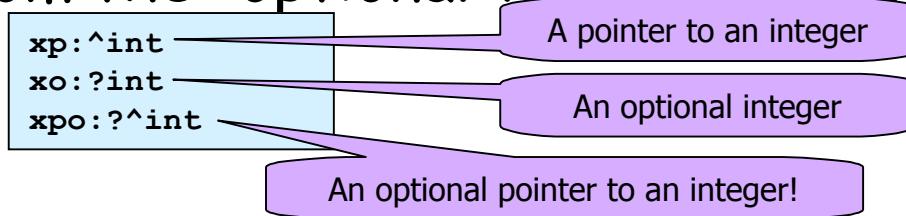
Explicit type/value dependency
between function parameters

```
Sum{n:nat} (xs:[n]int)=..  
a=Sum([7, 8, 9])
```



How might this work?

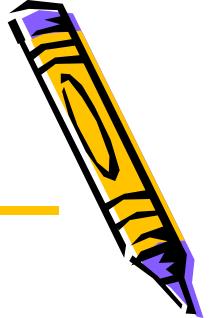
- Separating the “pointer to t ” concept from the “optional value of t ” concept



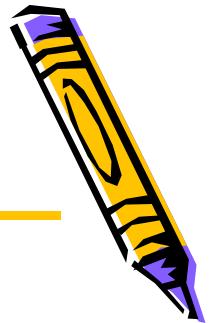
- Comprehensions (a la Haskell), for safely traversing and generating

col

```
Successors(xs: []int): []int=
  foreach(x in xs)
    x+1
```



How might this work?



A guarded casting mechanism for cases where need a safe "escape":

Here, we cast `i` to type of natural numbers bounded by the length of `as`, and bind the result to `n`

We can only access `i` within this context

If the cast fails, we execute the `else`-branch

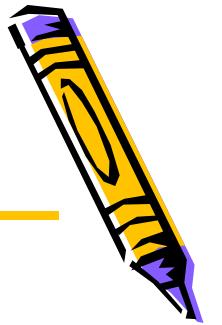
```
GetElement(as:[]string, i:int):string=
  if(n:nat<as.length=i)
    as[n]
  else
    "Index Out of Bounds"
```

All potential failure must be explicitly handled, but we lose no expressiveness.

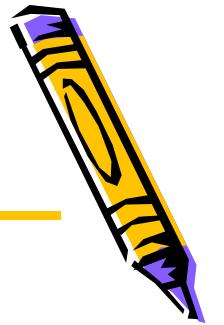


Analysis of the Unreal code

- Usage of integer variables in Unreal:
 - 90% of integer variables in Unreal exist to index into arrays
 - 80% could be dependently-typed explicitly, guaranteeing safe array access without casting.
 - 10% would require casts upon array access.
 - The other 10% are used for:
 - Computing summary statistics
 - Encoding bit flags
 - Various forms of low-level hackery
- “For” loops in Unreal:
 - 40% are functional comprehensions
 - 50% are functional folds



Accessing uninitialized variables



- Can we make this work?

```
class MyClass
{
    const int a=c+1;
    const int b=7;
    const int c=b+1;
}
MyClass myvalue = new C; // What is myvalue.a?
```

This is a frequent bug. Data structures are often rearranged, changing the initialization order.

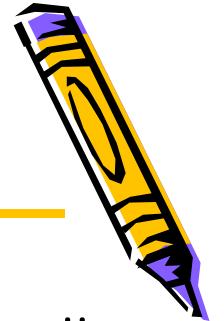
- Lessons from Haskell:
 - Lazy evaluation enables correct out-of-order evaluation
 - Accessing circularly entailed values causes thunk reentry (divergence), rather than just returning the wrong value



Lesson from Id90: Lenient evaluation is sufficient to guarantee this



Dynamic Failure: Conclusion



Reasonable type-system extensions could statically eliminate all:

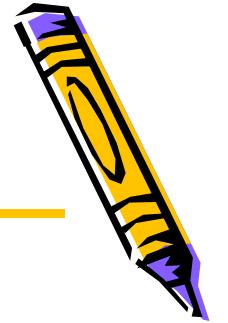
- Out-of-bounds array access
- Null pointer dereference
- Integer overflow
- Accessing of uninitialized variables

See Haskell for excellent implementation of:

- Comprehensions
- Option types via `Maybe`
- Non-NULL references via `IORef`, `STRef`
- Out-of-order initialization



Integer overflow



The Natural Numbers

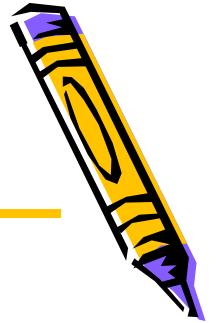
```
data Nat = Zero | Succ Nat
```

Factoid: C# exposes more than 10 integer-like data types, none of which are those defined by (Pythagoras, 500BC).

In the future, can we get integers right?



Can we get integers right?



Neat Trick:

- In a machine word (size 2^n), encode an integer $\pm 2^{n-1}$ or a pointer to a variable-precision integer
- Thus “small” integers carry no storage cost
- Additional access cost is ~ 5 CPU instructions

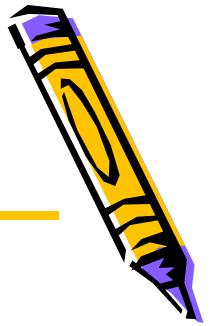
But:

- A natural number bounded so as to index into an active array is guaranteed to fit within the machine word size (the array is the proof of this!) and thus requires no special encoding.
- Since $\sim 80\%$ of integers can dependently-typed to access into an array, the amortized cost is ~ 1 CPU instruction per integer operation.

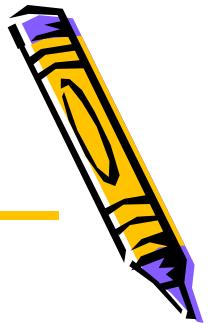
This could be a viable
tradeoff



Concurrency



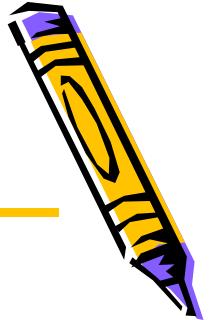
The C++/Java/C# Model: “Shared State Concurrency”



- The Idea:
 - Any thread can modify any state at any time.
 - All synchronization is explicit, manual.
 - No compile-time verification of correctness properties:
 - Deadlock-free
 - Race-free



The C++/Java/C# Model: “Shared State Concurrency”

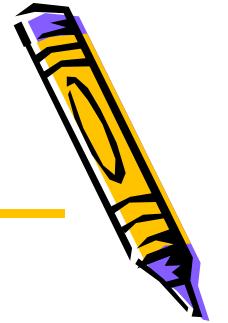


- This is hard!
- How we cope in Unreal Engine 3:
 - 1 main thread responsible for doing all work we can't hope to safely multithread
 - 1 heavyweight rendering thread
 - A pool of 4-6 helper threads
 - Dynamically allocate them to simple tasks.
 - “Program Very Carefully!”
- Huge productivity burden



Scales poorly to thread counts *There must be a better way!*

Three Kinds of Code: Revisited



- Gameplay Simulation
 - Gratuitous use of mutable state
 - 10,000's of objects must be updated
 - Typical object update touches 5-10 other objects
- Numeric Computation
 - Computations are purely functional
 - But they use state locally during computations



Shading

- Already implicitly data parallel

Concurrency in Shading



- Look at the solution of *CG/HLSL*:
 - New programming language aimed at "Embarassingly Parallel" shader programming
 - Its constructs map naturally to a data-parallel implementation
 - Static control flow (conditionals supported via masking)



Concurrency in Shading

Conclusion: The problem of *data-parallel* concurrency is effectively solved(!)



"Proof": Xbox 360 games are running with 48-wide data shader programs utilizing half a Teraflop of compute power...

Concurrency in Numeric Computation

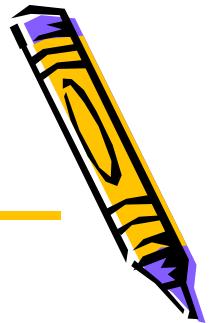


- These are essentially pure functional algorithms, but they operate locally on mutable state
- Haskell ST, STRef solution enables encapsulating local heaps and mutability within referentially-transparent code
- These are the building blocks for implicitly parallel programs
- Estimate ~80% of CPU effort in Unreal can be parallelized this way

In the future, we will write these algorithms using referentially-transparent constructs.



Numeric Computation Example: Collision Detection



A typical collision detection algorithm takes a line segment and determines when and where a point moving along that line will collide with a (constant) geometric dataset.

```
struct vec3
{
    float x,y,z;
};
struct hit
{
    bool DidCollide;
    float Time;
    vec3 Location;
};
hit collide(vec3 start,vec3 end);
```

```
Vec3  = data Vec3 float float float
Hit   = data Hit float Vec3
collide :: (vec3,vec3) -> Maybe Hit
```



Numeric Computation Example: Collision Detection



- Since `collisionCheck` is effects-free, it may be executed in parallel with any other effects-free computations.
- Basic idea:
 - The programmer supplies effect annotations to the compiler.
 - The compiler verifies the annotations

```
collide(start:Vec3,end:Vec3) : ?Hit  
print(s:string) [#imperative] : void
```

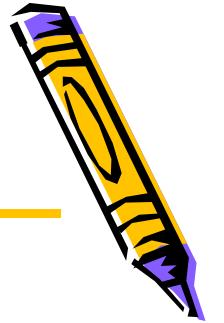
A pure function
(the default)

Effectful functions require
explicit annotations

- Many viable implementations (Haskell's Monadic effects, effect typing, etc)
In a concurrent world, imperative is the wrong default!



Concurrency in Gameplay Simulation



This is the hardest problem...

- 10,00's of objects
- Each one contains mutable state
- Each one updated 30 times per second
- Each update touches 5-10 other objects

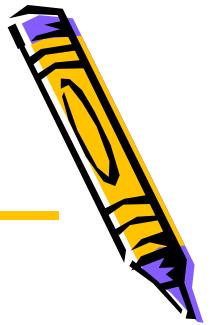
Manual synchronization (shared state concurrency)
is
hopelessly intractable here.

Solutions?



- Rewrite as referentially-transparent functions?
- Message-passing concurrency?

Concurrency in Gameplay Simulation: Software Transactional Memory



See "Composable memory transactions";
Harris, Marlow, Peyton-Jones, Herlihy

The idea:

- Update all objects concurrently in arbitrary order, with each update wrapped in an atomic {...} block
- With 10,000's of updates, and 5-10 objects touched per update, collisions will be low
- ~2-4X STM performance overhead is acceptable: if it enables our state-intensive code to scale to many threads, it's still a win



Claim: Transactions are the only plausible solution to concurrent mutable state



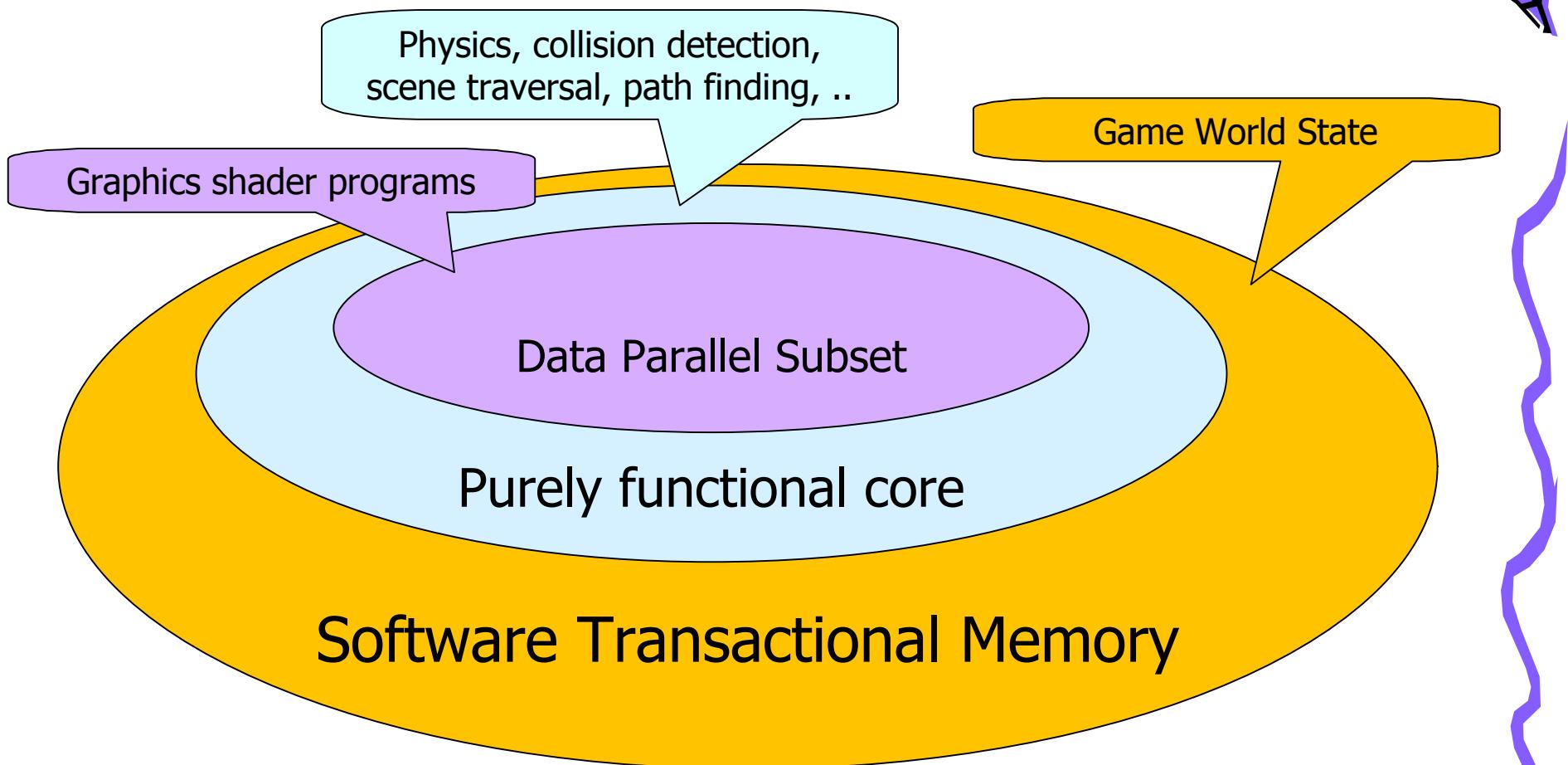
Three Kinds of Code: Revisited



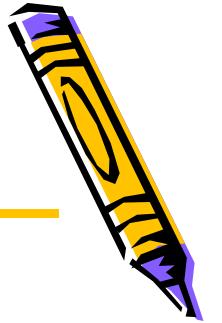
	Game Simulation	Numeric Computation	Shading
Languages	C++, Scripting	C++	CG, HLSL
CPU Budget	10%	90%	n/a
Lines of Code	250,000	250,000	10,000
FPU Usage	0.5 GFLOPS	5 GFLOPS	500 GFLOPS
Parallelism	Software Transactions Memory	Implicit Thread Parallelism	Implicit Data Parallelism



Parallelism and purity



L



Musings

On the Next Mainstream Programming Language



Musings



There is a wonderful correspondence between:

- Features that aid reliability
- Features that enable concurrency.

Example:

- Outlawing runtime exceptions through dependent types
 - Out of bounds array access
 - Null pointer dereference
 - Integer overflow

Exceptions impose sequencing constraints on concurrent execution.
*Dependent types and concurrency must
evolve simultaneously*



Language Implications



Evaluation Strategy

- Lenient evaluation is the right default.
- Support lazy evaluation through explicit suspend/evaluate constructs.
- Eager evaluation is an optimization the compiler may perform when it is safe to do so.



Language Implications



Effects Model

- Purely Functional is the right default
- Imperative constructs are vital features that must be exposed through explicit effects-typing constructs
- Exceptions are an effect

Why not go one step further and define partiality as an effect, thus creating a foundational language subset suitable for proofs?



Performance - Language Implications



Memory model

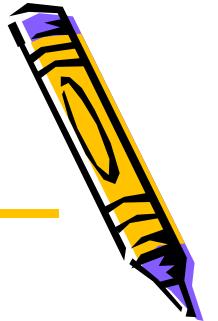
- Garbage collection should be the only option

Exception Model

- The Java/C# "exceptions everywhere" model should be wholly abandoned
 - All dereference and array accesses must be statically verifyable, rather than causing sequenced exceptions
- No language construct except "throw" should generate an exception



Syntax



Requirement:

- Must not scare away mainstream programmers.
- Lots of options.

```
int f{nat n}(int[] as, natrange<n> i)
{
    return as[i];
}
```

C Family: Least scary,
but it's a messy legacy

```
f :: forall n::nat. ([int], nat<n> -> int
f (xs, i) = xs !! i
```

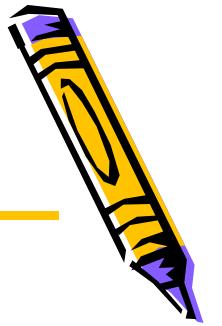
Haskell family: Quite scary :-)

```
f{nat n}(as:[int], i:nat<n>) = as[i]
```

Pascal/ML family:
Seems promising



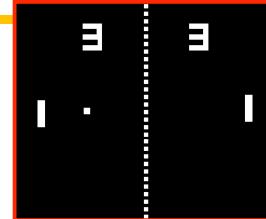
Conclusion



A Brief History of Game Technology



← 1972 Pong (hardware)



← 1993 DOOM (C)



← 1998 Unreal (C++, Java-style script)

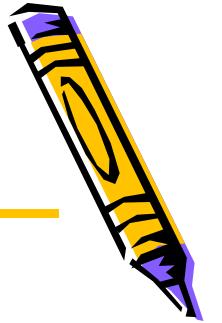


← 2005-6 Xbox 360, PlayStation 3
with 6-8 hardware threads



2009 Next console generation. Unification of the
CPU, GPU, memory, and I/O.

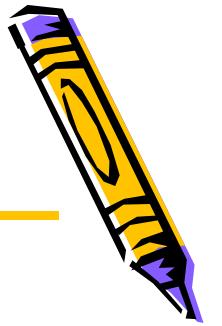
The Coming Crisis in Computing



- By 2009, game developers will face...
- CPU's with:
 - 20+ cores
 - 80+ hardware threads
 - >1 TFLOP of computing power
- GPU's with general computing capabilities.
- Game developers will be at the forefront.
- If we are to program these devices productively, you are our only hope!



Questions?



L

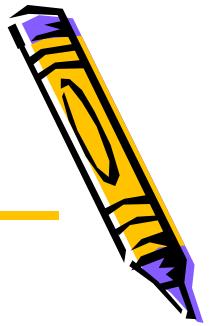


Backup Slides



The Genius of Haskell

- Algebraic Datatypes
 - Unions done right
Compare to: C unions, Java union-like class hierarchies
 - Maybe t
C/Java option types are coupled to pointer/reference types
- IO, ST
 - With STRef, you can write a pure function that uses heaps and mutable state locally, verifyably guaranteeing that those effects remain local.



The Genius of Haskell

■ Comprehensions

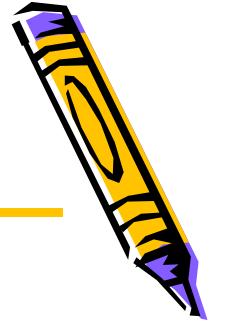
Sorting in Haskell

```
sort []      = []
sort (x:xs) = sort [y | y<-xs, y<x ] ++
              [x
               ] ++
              sort [y | y<-xs, y>=x]
```

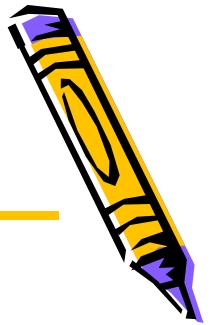


Sorting in C

```
int partition(int y[], int f, int l);
void quicksort(int x[], int first, int last) {
    int pivIndex = 0;
    if(first < last) {
        pivIndex = partition(x,first, last);
        quicksort(x,first,(pivIndex-1));
        quicksort(x,(pivIndex+1),last);
    }
}
int partition(int y[], int f, int l) {
    int up,down,temp;
    int cc;
    int piv = y[f];
    up = f;
    down = l;
    do {
        while (y[up] <= piv && up < l) {
            up++;
        }
        while (y[down] > piv ) {
            down--;
        }
        if (up < down ) {
            temp = y[up];
            y[up] = y[down];
            y[down] = temp;
        }
    } while (down > up);
    temp = piv;
    y[f] = y[down];
    y[down] = piv;
    return down;
}
```



Why Haskell is Not My Favorite Programming Language



- The syntax is ... scary
- Lazy evaluation is a costly default
 - But eager evaluation is too limiting
 - Lenient evaluation would be an interesting default
- Lists are the syntactically preferred sequence type
 - In the absence of lazy evaluation, arrays seem preferable



Why Haskell is Not My Favorite Programming Language



- Type inference doesn't scale
 - To large hierarchies of open-world modules
 - To type system extensions
 - To system-wide error propagation

```
f(x,y) = x+y  
a=f(3,"4")
```

...

```
ERROR - Cannot infer instance  
*** Instance    : Num [Char]  
*** Expression  : f (3,"4")
```

???

```
f(int x,int y) = x+y  
a=f(3,"4")
```

...

```
Parameter mismatch parameter 2 of call to f:  
  Expected: int  
  Got:       "4"
```

